

# Macroscopical Entangled Coherent State Generator in V configuration atom system

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In this paper, we propose a scheme to produce pure and macroscopical entangled coherent state. When a three-level "V" configuration atom interacts with a doubly resonant cavity, under the strong classical driven condition, entangled coherent state can be generated from vacuum fields. An analytical solution for this system under the presence of cavity losses is also given.

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## I. INTRODUCTION

The generation of Schrödinger cat states and entangled coherent states serves the first step to use coherent states in quantum information processes such as quantum sweeping and quantum teleportation[1]. Numerous schemes have been proposed to generate such an entangled coherent state[2–4, 6–10]. A scheme based on a double electromagnetically induced transparency system has been proposed in reference[2]. As for ion trap systems, the vibrational motion of ions[3] and the entanglement swapping[4] seems promising to generate an entangled coherent state. Using Kerr nonlinearity and a 50/50 beam splitter, multidimensional entangled coherent states can be generated on the condition that the initial state is a coherent state and the interaction times are within certain range[5].

Cavity quantum electrodynamics (QED) has been shown to be a convenient environment to generate both Schrödinger cat states[6, 7] and entangled coherent states[8] in early days. Recently, Solano *et al.* proposed a scheme to entangle two cavity modes through the interaction of the cavity modes with a system of  $N$  two-level atoms inside the cavity[9]. In their scheme, the two cavity modes interact with the same atomic transition and will put some restrictions on these two cavity modes.

On the other hand, atomic coherence, which results from the coherent superposition of different quantum states, can lead to many novel phenomena. These include correlated spontaneous emission laser (CEL)[10], lasing without inversion[11] and electromagnetically induced transparency[12] *etc.*. It has been known that two cavity modes can be entangled when they interact with three-level atoms [10, 13] and atomic coherence plays an essential role in this entanglement generation[14, 15]. Ref.[14] showed that the two-mode macroscopically entangled continuous-variable state could be created in a CEL system where the atomic coherence was induced by a classical driving field. Ref.[15] studied the interaction

of a "V" type three-level atom and two thermal modes of a doubly resonant cavity and showed that given a small amount of atomic coherence, entanglement could be generated between these two thermal modes even when they initially had arbitrarily high temperatures. However, the question whether an entangled coherent state of two cavity modes can be generated through the interaction with a single three-level atom has still not been answered there. Most recently, our group have investigated that under large detuning condition, a "λ" three-level atom system interacting with two-mode field can entangle the two-mode field[16]. The main drawback of the schemes [5, 16] is that the initial coherent state are demand, and the interaction time should be controled accurately otherwise we can not obtain entangled coherent state.

In this paper, we propose a scheme to generate a macroscopic entangled coherent state through the resonant interaction of two-mode field and a three level "V" (or "λ") configuration atom. Comparing this scheme with Ref.[5, 16], we do not need prepare the initial coherent state field state while the amplitude of entangled coherent state can be amplified, which means the system can work as a entanglement generator. Also, we do not need to control the interaction time accurately. It just affect the amplitude of the entangled coherent state and have no effect on the entanglement. Comparing our scheme with that of Refs[9], the two cavity modes in our scheme interact with different atomic transitions, and thus can be easily manipulated.

## II. THE THEORY AND THE SCHEME DESCRIPTION

We consider a three-level atom in the "V" or "λ" configuration crossing a doubly resonant cavity. Here, we will take "V" configuration atom as example, and all of the calculation can be easy generalized to "λ" configuration atom. The atomic level configuration is depicted

in Fig.1. The atom resonantly interacts with two cavity modes and two classical driving fields.  $g_1$  and  $g_2$  are two different atom-field coupling constants and  $\Omega_1$ ,  $\Omega_2$  are the Rabi frequencies of the corresponding classical driving fields.

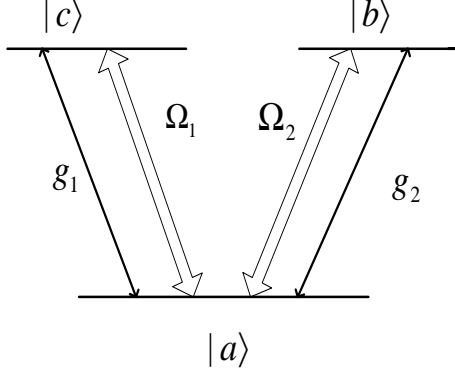


FIG. 1: The energy level configuration of the atom. Two cavity modes resonantly interact with atomic transition  $|c\rangle \leftrightarrow |a\rangle$  and  $|b\rangle \leftrightarrow |a\rangle$  while two classical fields drive the two atomic transitions.

In the interaction picture, the interaction Hamiltonian has the following form under the rotating-wave approximation

$$H = H_0 + H_1 \quad (1)$$

where

$$H_0 = \Omega_1(|c\rangle\langle a| + |a\rangle\langle c|) + \Omega_2(|b\rangle\langle a| + |a\rangle\langle b|), \quad (2)$$

$$H_1 = g_1(a_1|c\rangle\langle a| + a_1^\dagger|c\rangle\langle a| + g_2(a_2|b\rangle\langle a| + a_2^\dagger|a\rangle\langle b|). \quad (3)$$

It is convenient to solve this system in a dressed state picture with respect to the two strong classical driving fields. For this, we diagonalize  $H_0$ . The eigenstates and corresponding eigenvalues of  $H_0$  are

$$\begin{aligned} |A\rangle &= \frac{1}{u}(-\Omega_1|b\rangle + \Omega_2|c\rangle), \lambda_1 = 0, \\ |B\rangle &= \frac{1}{\sqrt{2}u}[u|a\rangle + \Omega_2|b\rangle + \Omega_1|c\rangle], \lambda_2 = u, \\ |C\rangle &= \frac{1}{\sqrt{2}u}[-u|a\rangle + \Omega_2|b\rangle + \Omega_1|c\rangle], \lambda_3 = -u, \end{aligned} \quad (4)$$

where

$$u = \sqrt{\Omega_1^2 + \Omega_2^2}.$$

It is easy to prove that states  $|A\rangle$ ,  $|B\rangle$  and  $|C\rangle$  compose a new orthogonal and complete basis of the three level

system. Under this basis, the atomic states can be written as

$$\begin{aligned} |a\rangle &= \frac{1}{\sqrt{2}}(|B\rangle - |C\rangle), \\ |b\rangle &= \frac{1}{\sqrt{2}u}[-\sqrt{2}\Omega_1|A\rangle + \Omega_2(|B\rangle + |C\rangle)], \\ |c\rangle &= \frac{1}{\sqrt{2}u}[\sqrt{2}\Omega_2|A\rangle + \Omega_1(|B\rangle + |C\rangle)], \end{aligned} \quad (5)$$

We can then rewrite Hamiltonian Eq.(1) under this new basis set and perform the following unitary transformation  $H_I = e^{iH_0t}H_1e^{-iH_0t}$ . We have

$$\begin{aligned} H_I &= \frac{1}{2u}\{g_1a_1[\Omega_1(|B\rangle\langle B| - |C\rangle\langle C| \\ &\quad - |B\rangle\langle C|e^{-2uti} + |C\rangle\langle B|e^{2uti}) \\ &\quad + \sqrt{2}\Omega_2(e^{uti}|A\rangle\langle B| - |A\rangle\langle C|e^{-uti})] \\ &\quad + g_2a_2[\Omega_2|B\rangle\langle B| - |C\rangle\langle C| \\ &\quad - |B\rangle\langle C|e^{-2uti} + |C\rangle\langle B|e^{2uti} \\ &\quad - \sqrt{2}\Omega_1(e^{uti}|A\rangle\langle B| - |A\rangle\langle C|e^{-uti})] + h.c.\} \end{aligned} \quad (6)$$

In strong driving regime, that is  $\Omega_1(\Omega_2) \gg g_1(g_2)$ , we can realize a secular approximation (i.e. rotating-wave approximation) and eliminate the high frequency terms in Eq.(6)[9]. The effective Hamiltonian under this approximation is

$$H_{eff} = \frac{1}{2u}[\Omega_1g_1(a_1 + a_1^\dagger) + \Omega_2g_2(a_2 + g_2a_2^\dagger)](|B\rangle\langle B| - |C\rangle\langle C|). \quad (7)$$

If our initial state of the atom field combined system is  $|\Psi(0)\rangle = |a, 0, 0\rangle$ . By using Hamiltonian Eq.(7), we can have the state of the system as

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}}(|B, \alpha, \beta\rangle - |C, -\alpha, -\beta\rangle) \quad (8)$$

where  $\alpha = \frac{-i\Omega_1g_1t}{2u}$  and  $\beta = \frac{-i\Omega_2g_2t}{2u}$ . We now apply the inverse unitary transformation on state Eq.(8) and change the basis set back to original atomic states, and we have

$$\begin{aligned} |\Psi(t)\rangle &= \frac{1}{\sqrt{2}}[\sqrt{2}|a\rangle(e^{-iut}|\alpha, \beta\rangle + e^{iut}|\alpha, -\beta\rangle) \\ &\quad + |b\rangle(e^{-iut}|\alpha, \beta\rangle - e^{iut}|\alpha, -\beta\rangle) \\ &\quad + |c\rangle(e^{-iut}|\alpha, \beta\rangle - e^{iut}|\alpha, -\beta\rangle)]. \end{aligned} \quad (9)$$

When the atom comes out from the two mode cavity, we can use level-selective ionizing counters to detect the atomic state. If the internal state of atom is detected to be  $|b\rangle$ ,  $|c\rangle$  or  $|a\rangle$ . The two-mode field will be projected into

$$|\Psi(t)\rangle_{f\pm} = \frac{1}{\sqrt{M_\pm}}[e^{-iut}|\alpha, \beta\rangle \pm e^{iut}|\alpha, -\beta\rangle], \quad (10)$$

where

$$M_\pm = 2[1 \pm \cos 2ut \exp(-2|\alpha|^2 - 2|\beta|^2)]. \quad (11)$$

The state Eq.(10) is a normalized one. The average photon number of the two modes of the cavity can be easily obtained as

$$\langle N_1 \rangle = \frac{2|\alpha|^2}{M}(1 \mp e^{-2|\alpha|^2-2|\beta|^2} \cos 2ut), \quad (12)$$

$$\langle N_2 \rangle = \frac{2|\beta|^2}{M}(1 \mp e^{-2|\alpha|^2-2|\beta|^2} \cos 2ut). \quad (13)$$

We now try to estimate the entanglement of state Eq.(10). We notice that for a general normalized and nonorthogonal entangled coherent state

$$|\Psi\rangle = \mu|\bar{\alpha}, \bar{\beta}\rangle + \nu|\bar{\gamma}, \bar{\delta}\rangle, \quad (14)$$

we can define  $|0\rangle = |\bar{\alpha}\rangle$ ,  $|1\rangle = (|\bar{\gamma}\rangle - p_1|\bar{\alpha}\rangle)/\sqrt{1-|p_1|^2}$  with  $p_1 = \langle \bar{\alpha}|\bar{\gamma}\rangle$  for the first subsystem and define  $|0\rangle = |\bar{\beta}\rangle$ ,  $|1\rangle = (|\bar{\delta}\rangle - p_2|\bar{\beta}\rangle)/\sqrt{1-|p_2|^2}$  with  $p_2 = \langle \bar{\beta}|\bar{\delta}\rangle$  for the second subsystem. The entanglement of state Eq.(14) can be measured on the orthogonal basis  $|0,0\rangle$ ,  $|0,1\rangle$ ,  $|1,0\rangle$  and  $|1,1\rangle$  [4, 17]. We recall that the concurrence of state can be used to estimate the entanglement for such a state. The concurrence [18] of a state is defined as  $C = \max(0, 2\max \lambda_i - \sum_{i=1}^4 \lambda_i)$  where  $\lambda_i$  is the square roots of the eigenvalues of the matrix  $R = \rho(\sigma_1^y \otimes \sigma_2^y)\rho^*(\sigma_1^y \otimes \sigma_2^y)$  and  $\sigma_i^y$  is Pauli matrices. The concurrence of state Eq.(14) is [4, 17]

$$C = 2|\mu\nu|\sqrt{(1-|p_1|^2)(1-|p_2|^2)}. \quad (15)$$

Whenever  $C > 0$ , state Eq.(14) is an entangled state. The concurrence of the state generated from our system (Eq.10) is

$$C = \frac{\sqrt{[(1 - \exp(-4|\alpha|^2))][(1 - \exp(-4|\beta|^2))]}{1 \pm \cos 2ut \exp(-2|\alpha|^2 - 2|\beta|^2)}. \quad (16)$$

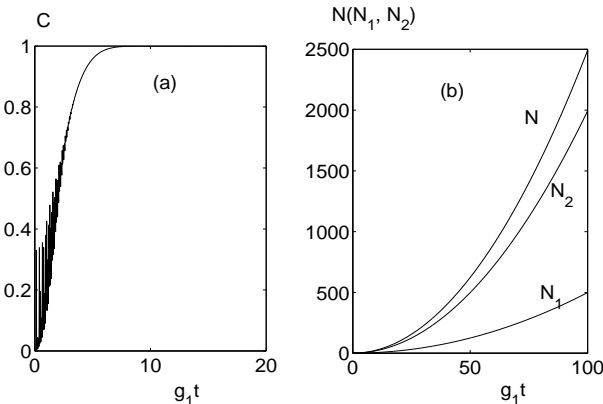


FIG. 2: The time evolution for entanglement and average photon number. In Fig.2b, the lines labeled with  $N, N_1, N_2$  correspond to total, mode 1, mode 2 average photon number, respectively. The parameters are  $g_1 = g_2 = 1$ ,  $\Omega_1 = 100$ ,  $\Omega_2 = 200$ .

Fig.2 shows the time evolution of concurrence (Eq.(16)) and the average total photon number (Eqs.(12) and (13)) of our state. Here, the positive sign has been chosen for Eq.(16) and negative sign has been chosen for Eqs.(12) and (13). As we have analyzed in [19], due to the phase  $e^{\pm iut}$ , the state  $|\Psi(t)\rangle_{f+}$  and  $|\Psi(t)\rangle_{f-}$  almost have no difference. One can see it from the expression of Eq.(15). The high frequency term related with  $\cos 2ut$  actually can be ignored. The property is different from the two state  $\frac{1}{\sqrt{N}}(|\alpha, \alpha\rangle \pm |-\alpha, -\alpha\rangle)$  [20], where  $\frac{1}{N_-}(|\alpha, \alpha\rangle - |-\alpha, -\alpha\rangle)$  is exact one ebit and its entanglement is always 1 while  $\frac{1}{N_+}(|\alpha, \alpha\rangle + |-\alpha, -\alpha\rangle)$  is maximum state only when  $\alpha \rightarrow \infty$ . From the Fig.2, we see that during short time evolution concurrence curve show high frequency oscillation which come from classical field. As time elapse, entanglement and average photon number increase. The entanglement reaches its maximum value 1 after a specific time and in the mean time we can obtain large number of photons in the cavity. This can be understood clearly from Eq.(16). If  $\alpha$  and  $\beta$  are large enough,  $\alpha$  and  $-\alpha$ ,  $\beta$  and  $-\beta$  will be orthogonal, i.e.,  $\langle \alpha | -\alpha \rangle = \exp(-2|\alpha|^2) = 0$ ,  $\langle \beta | -\beta \rangle = \exp(-2|\beta|^2) = 0$  so that the state equal to  $\frac{1}{\sqrt{2}}(|0,0\rangle + |1,1\rangle)$ . Therefore concurrence  $C = 1$ . One also see that  $\alpha$  and  $\beta$  with increase with respect to time, the average photon number is thus increased.

### III. THE TWO-MODE FIELD IN THE LEAK CAVITIES

In order to obtain analytic solution of density matrix, here we do not consider the atomic level decay. We now consider the effects of cavity losses upon the entanglement generation of the two mode field. The master equation is

$$\dot{\rho} = -i[H_{eff}, \rho] + \kappa(2a_1\rho a_1^\dagger - a_1^\dagger a_1\rho - \rho a_1^\dagger a_1 + 2a_2\rho a_2^\dagger - a_2^\dagger a_2\rho - \rho a_2^\dagger a_2) \quad (17)$$

For simplicity, we assume the two modes have the same cavity decay rates  $\kappa$ . We still assume the atom is initially injected into state  $|a\rangle$ . Thus, we only need to work on the subspace  $|B\rangle$  and  $|C\rangle$ . Using superoperator technique [21] and Hausdorff similarity transformation [22], we deduce that

$$\begin{aligned} \rho = & |B, \alpha', \beta'\rangle\langle B, \alpha', \beta'| \\ & + |C, -\alpha', -\beta'\rangle\langle C, -\alpha', -\beta'| \\ & - q(e^{-2uit}|B, \alpha', \beta'\rangle\langle C, -\alpha', -\beta'| \\ & + e^{2uit}|C, -\alpha', -\beta'\rangle\langle B, \alpha', \beta'|) \end{aligned} \quad (18)$$

where

$$\begin{aligned} \alpha' &= \frac{-i\Omega_1 g_1}{2u\kappa}(1 - e^{-\kappa_1 t}), \beta' = \frac{-i\Omega_2 g_2}{2u\kappa}(1 - e^{-\kappa_2 t}), \\ q &= \exp\left[-\frac{\Omega_1^2 g_1^2 + \Omega_2^2 g_2^2}{2u^2 \kappa^2}(2\kappa t + 4e^{-\kappa t} - e^{-2\kappa t} - 3)\right] \end{aligned} \quad (19)$$

with  $P_1 = \exp(-2|\alpha'|^2)$ ,  $P_2 = \exp(-2|\beta'|^2)$ . In the process of calculation Eq.(19), we need successively use the operator disentangle equation  $\exp(A+B) = \exp[\frac{A(1-e^{-\eta})}{\eta}] \exp(B) = \exp(B) \exp[\frac{A(e^\eta-1)}{\eta}]$  if  $[A, B] = \eta A$ . After the atom comes out from the cavity, we measure the atomic state again. Suppose the internal state of the atom is detected to be in  $|a\rangle$ , the two-mode field will be projected into

$$\begin{aligned} \rho = & \frac{1}{S} [ |\alpha', \beta'\rangle \langle \alpha', \beta'| \\ & + qe^{-2uit} |\alpha', \beta'\rangle \langle -\alpha', -\beta'| \\ & + qe^{2uit} |-\alpha', -\beta'\rangle \langle \alpha', \beta'| \\ & + |-\alpha', -\beta'\rangle \langle -\alpha', -\beta'| ] \end{aligned} \quad (20)$$

with

$$S = 2 + 2qP_1P_2 \cos 2ut.$$

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$$\rho = \frac{1}{S} \begin{pmatrix} 1 + P_1^2 P_2^2 + 2qP_1P_2 \cos 2ut & P_1M_2(P_1P_2 + qe^{-2iut}) & P_2M_1(P_1P_2 + qe^{-2iut}) & M_1M_2(P_1P_2 + qe^{-2iut}) \\ P_1M_2(P_1P_2 + qe^{2iut}) & P_1^2 M_2^2 & M_1M_2P_1P_2 & P_1M_1M_2^2 \\ P_2M_1(P_1P_2 + qe^{2iut}) & M_1M_2P_1P_2 & P_2^2 M_1^2 & P_2M_1^2M_2 \\ M_1M_2(P_1P_2 + qe^{2iut}) & P_1M_1M_2^2 & M_1^2 M_2P_2 & M_1^2 M_2^2 \end{pmatrix} \quad (21)$$


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Although the density matrix  $\rho$  is very tedious, the eigenvalues of  $R$  and concurrence still can be evaluated. The concurrence is

$$C = \frac{2M_1M_2}{S} q. \quad (22)$$

One can easily check that without the loss of the cavity, the factor  $q$  will be 1 and the expression Eq.(22) will be the same as Eq.(16) for positive sign. The average photon number for the two modes can be obtained as

$$\begin{aligned} N_1 &= \frac{2|\alpha'|^2}{S} (1 - qP_1P_2 \cos 2ut), \\ N_2 &= \frac{2|\beta'|^2}{S} (1 - qP_1P_2 \cos 2ut). \end{aligned} \quad (23)$$

Fig.3 shows the time evolution of the concurrence and the total average photon number  $N = N_1 + N_2$  of the two-mode cavity under the presence of cavity losses. Not surprisingly the average photon number of the two-mode field will decrease with the increasing of  $\kappa$ . The concurrence increases first and then drops down to zero. The reason of concurrence dropping comes from the factor  $q$ . With time going,  $q$  will be smaller and smaller so that entanglement is destroyed. Therefore, in our scheme, high-Q doubly resonant cavity is preferred.

Now the field state is in a mixed entangled state. The difference between the state Eq.(10) and Eq.(20) mainly lies in the factor of  $q$  except for the change of coherent amplitude  $\alpha'$ . Here  $q$  is the key factor to destroy the entanglement. With the time evolution,  $q$  will achieve its asymptotic value zero so that the entanglement will be destroyed completely. If there are no cavity losses,  $q$  will be 1, therefore the state Eq.(20) will be exactly the same as Eq.(10).

To measure the entanglement, we will still use Concurrence. Let  $|0\rangle = |\alpha'\rangle$ ,  $|1\rangle = (|-\alpha'\rangle - P_1|\alpha'\rangle)/M_1$  with  $P_1 = \langle \alpha' | -\alpha' \rangle = \exp(-2|\alpha'|^2)$ ,  $M_1 = \sqrt{1 - |P_1|^2}$  for field 1, and  $|0\rangle = |\beta'\rangle$ ,  $|1\rangle = (|-\beta'\rangle - P_2|\beta'\rangle)/M_2$  with  $P_2 = \langle \beta' | -\beta' \rangle = \exp(-2|\beta'|^2)$ ,  $M_2 = \sqrt{1 - |P_2|^2}$  for field 2. The density matrix of the fields will be

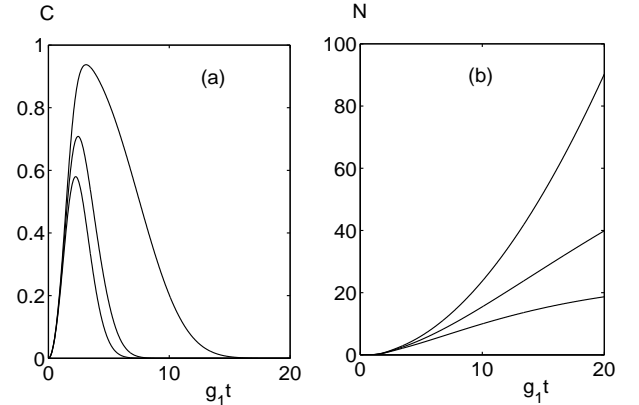


FIG. 3: The time evolution of entanglement and average photon number for the loss of cavity  $g_1 = g_2 = 1$ ,  $\Omega_1 = 200$ ,  $\Omega_2 = 200$ . From top to bottom for Fig.3a and 3b,  $\kappa = 0.005, 0.05, 0.1$ , respectively.

#### IV. DISCUSSION AND CONCLUSION

We now briefly address the experimental feasibility of the proposed scheme. The required atomic level configuration can be achieved in Rydberg atoms circular atomic level[23]. The radiative lifetime is about  $3 \times 10^{-2} s$ —are much longer than those for noncircular Rydberg states[24]. Even in free space, the atoms would prop-

agate a few meters at thermal velocity before decaying. So, atomic radiative decay is thus negligible along the 20-cm path inside the apparatus (In our model, we do not consider the atomic spontaneous decay, therefore circular level Rydberg atom is a good choice). For circular Rydberg atom, the coupling constant is  $g = 2\pi \times 24k\text{Hz}$ , if the interacting time  $t \simeq 6.6 \times 10^{-4}\text{s}$  (much smaller than the radiative lifetime  $3 \times 10^{-2}\text{s}$ ),  $gt \sim 100$  correspond to the maximum value in Fig.2b, the coherent state  $\alpha = \frac{-i\Omega_1 g_1 t}{2u} \sim -35i$  (for  $\Omega_1 = \Omega_2$ ). Considering the loss of the cavity,  $\alpha' = \frac{-i\Omega_1 g_1}{2u\kappa}(1 - e^{-\kappa_1 t}) \sim -15.6i$  (for  $\Omega_1 = \Omega_2, \kappa = 0.05$ ). Therefore, based on a cavity QED techniques presently, the proposed scheme might be realizable. As to the atomic projecting detection, if the upper two atomic levels  $|c\rangle$  and  $|b\rangle$  are not degenerate, when the atom comes out from cavity, the three field-ionization detector  $D_c$ ,  $D_b$  and  $D_a$  can be used for the three levels respectively. If the atomic lifetime is not long enough, one must include the decay of the excited atomic level. The analytic solution can not be obtained. One can numerically solve it. Definitely, the decay of the

atom will be bad for coherence of the system. In order to obtain strong entanglement, high-Q doubly-resonant cavity and long lifetime atom should be a first choice.

In conclusion, by employing a three-level "V" configuration atom interacting with a two-mode cavity field, under the strong driven condition, we can produce entangled coherent state from vacuum state, which means the system can work as entanglement generator. The average photon number of the two-mode cavity can be large. The scheme has its advantages. we do not need to control the interacting time accurately. It just affect the amplitude of the entanglement and have no effect on the entanglement. The two cavity modes interact with different atomic transition so that it is easy to driven two classical fields separately. The produced entangled coherent state can be easily differentiated just by differentiable polarization.

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